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Amplification of photoelectric injection in the photodiode based on large-grain cadmium telluride films

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Abstract. The results of studying amplification of photoelectric injection in the Al–Al_2O_3–*p*-CdTe–Mo structure at high bias voltages for the forward current have been presented. It has been shown that the spectral sensitivity reaches its maximum value $S_\lambda = 8.4 \cdot 10^4$ A/W, when the diode is illuminated with the “own” light at λ = 450 nm and V = 7 V, while when it is illuminated with the “impurity” light at λ = 950 nm $S_\lambda = 4.3 \cdot 10^4$ A/W under the same bias voltage. It has been ascertained that when illuminating the structure with the “own” light, the positive feedback mechanism is realized, and when illuminating with “impurity” light, the parametric amplification mechanism is realized.

Keywords: semiconductor film, photodetector, sensitivity, current-voltage characteristics.

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1. Introduction

At present, photodiodes are widely used in photometric registration and measuring devices, cinema equipment, photo telegraphy, *etc*. A significant drawback of them is low current photosensitivity, since their quantum yield cannot exceed unity. Use of photodiodes in the avalanche multiplication mode is possible only under very stringent requirements on temperature stability and value of supply voltage. Injection photodiodes (IPDs), which are a new class of internal-amplification photodetectors, are devoid of these shortcomings. IPDs were mainly fabricated using Ge, Si and GaAs, which enables an effective operation at low temperatures. A disadvantage of these photodiodes is limitation of their spectral sensitivity by the one of materials they are made of. From this point of view, creation of injection photodetectors based on A^2B^6 seems to be a promising goal. A^2B^6 materials have band gaps covering the entire visible and part of ultraviolet spectral range. They are characterized by direct optical transitions, which enable to obtain high efficiency of electron-hole pair generation. Pursuing the mentioned goal implies formulation of the purpose of this work.

p-CdTe films with columnar grains were deposited onto Mo substrates by sublimation in a hydrogen flow. These films had the resistivity $\rho \approx 10^9 \ldots 10^{11}\ \Omega \cdot$cm and the minority carrier lifetime $\tau \sim 10^{-8} \ldots 10^{-7}$ s. A metal-oxide-semiconductor (MOS) structure was created on the surface of obtained *p*-CdTe films by sputtering aluminum in vacuum (~ 10^{-5} Torr) [1]. X-ray diffraction analysis showed [2, 3] that the Al_2O_3 layer with the thickness close to 30 nm grew in the technological process leading to formation of the Al–Al_2O_3–*p*-CdTe MOS structure.

This work is aimed at studying the mechanisms providing amplification of injection in the Al–Al_2O_3–*p*-CdTe–Mo structures at high current densities.

2. Samples and measurement procedures

To determine the efficiency of photon registration by the considered structure, we studied its spectral sensitivity (S_λ) in the absence of bias and calculated S_λ for an ideal photodetector (IP) within the wavelength range of 400…1000 nm [4]. The spectral photosensitivity of our structure was measured by 3MP-3 monochromator at room temperature (300 K). The radiation power was calibrated in absolute units by using a thermocouple with a silica window of the RNT-10 type. We call an ideal photodetector the one absorbing all incident photons with generation of electron-hole pairs, which are separated by a potential barrier without losses and contribute to the photocurrent. The value of parameter $S_{\lambda\, id}$ for an ideal photodetector was calculated using the formula $(e/h\nu)\, \lambda\eta_\lambda (1 - R)$, where η_λ is the internal quantum output and R is the reflection coefficient, respectively.

The values $\eta_\lambda = 1$ and $R = 0$ were taken for calculations. It was shown that the studied structure acts as an injection photodetector and amplifies the primary photocurrent even in the absence of external bias voltage. It was found that the spectral sensitivity at $\lambda = 450$ nm is $S_\lambda \approx 0.93$ A/W, which is 2.3 times greater than $S_{\lambda\, id}$ of ideal photodetector at the given wavelength. $S_\lambda \approx 1.1$ A/W at $\lambda = 750$ nm, which makes the ratio $S_\lambda/S_{\lambda\,\mathrm{id}} \approx 1.85$.

3. Experimental results and discussion

It is known that injection photodetectors can operate according to two amplification mechanisms, namely: positive feedback (PF) [5, 7] and parametric amplification (PA) [5, 6].

The results of studying the spectral dependence of photocurrent I_{ph} and spectral sensitivity S_λ do not allow us to say unequivocally, which of the primary photocurrent amplification mechanisms is realized in the studied samples. This question is answered by studying the dependences $I_{ph}(\lambda)$ and $S_\lambda(\lambda)$ when a bias voltage is applied to the structure. Therefore, the dependences $I_{ph}(\lambda)$, $S_\lambda(\lambda)$ at a small bias voltage applied to the structure were studied in [8]. The obtained results demonstrated that integral and spectral photosensitivity at higher current densities should be considered to determine the possibility of increasing the bipolar drift mobility by modulation of the filling of deep levels for capture of electrons in the studied Al–Al_2O_3–*p*-CdTe–Mo structure as well as to determine the relationship between the amplification factor of primary current and the magnitude of the dark current.

In Fig. 1, spectral distributions of the photosensitivity of our structure at various injection levels are shown. It follows from this figure that the spectral sensitivity increases within the entire range (400…1000 nm) with the increase of forward bias voltage. It should be noted that the dependence of S_λ on V varies in a very complicated way. For example, the spectral sensitivity is low within the entire spectral range up to the values of bias voltage $V \approx 0.01…0.4$ V, much lower than the value of S_λ of an ideal photodetector. However, S_λ begins to increase rapidly at $V \approx 0.4$ V and exceeds the photosensitivity of an ideal photodetector by a thousand or even hundred thousand times, depending on the spectral range, at the bias voltage of 6 V. In this case, S_λ usually increases by about hundred thousand times within the range of “intrinsic” absorption and by ten thousand times or more within the range of “impurity” absorption, respectively. We have demonstrated that the primary photocurrent is amplified within both the “intrinsic” and “impurity” absorption ranges. However, the laws for the dependence of spectral sensitivity on current are not clear in our case.

To clarify this issue, the current-voltage characteristics in the darkness and under illumination of the structure as well as the dependence of current sensitivity on bias voltage were jointly studied. First, we considered the effect of illumination with monochromatic light of the wavelengths from the “intrinsic” absorption range. For this, *I–V* characteristics in the darkness and under light illumination light ($\lambda = 650$ nm) were measured (Fig. 2a), and the dependence of S_λ on V was plotted (Fig. 2b). Figs. 2a and 2b show that the light and dark current-voltage characteristics are described with the same laws, and variation of S_λ with V corresponds to the laws of light *I–V* characteristics. The current-voltage characteristic in the darkness has four segments, which are described by the power-law dependences of current on the bias voltage, $J \sim V^\alpha$, with different values of α. In [9], such a sequence in a *I–V* characteristic was explained by a change in the conditions of recombination process. First, recombination occurs through simple local centers. At high current densities, it takes place through composite complexes, inside which an exchange of non-equilibrium carriers occurs. In particular, the linear segment with $J \sim V$ and the next one with $J \sim V^2$ are well explained by recombination through simple local impurity centers. However, the following segment with a

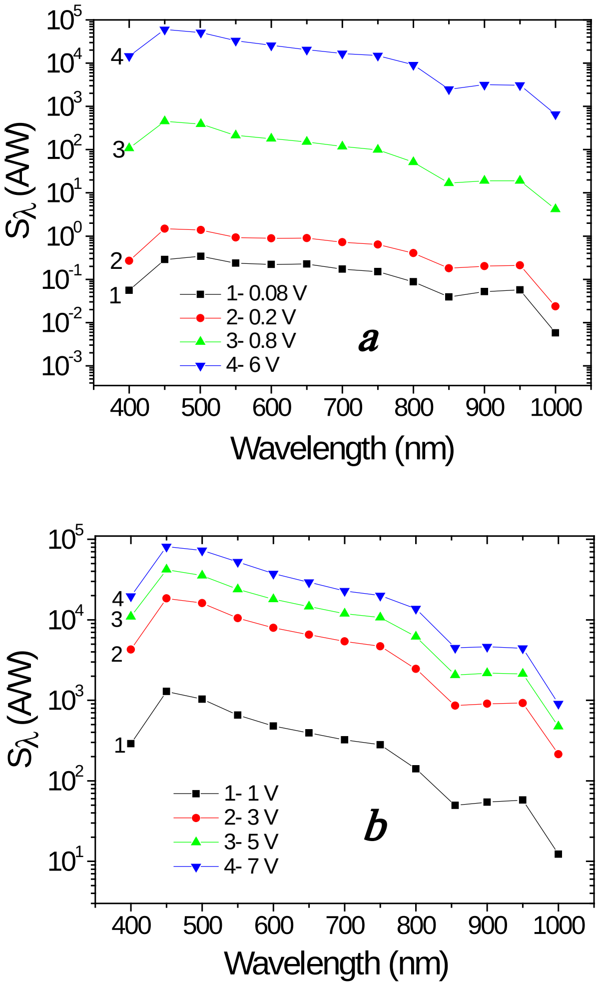

Fig. 1. Spectral sensitivity of the Al–n^+-Al_2O_3–*p*-CdTe–*n*-MoO_3–Mo structure at forward bias. Bias voltage V, *V*: a) *1* – 0.08, *2* – 0.2, *3* – 0.8, *4* – 6; b) *1* – 1, *2* – 3, *3* – 5, *4* – 7. *T* = 300 K.

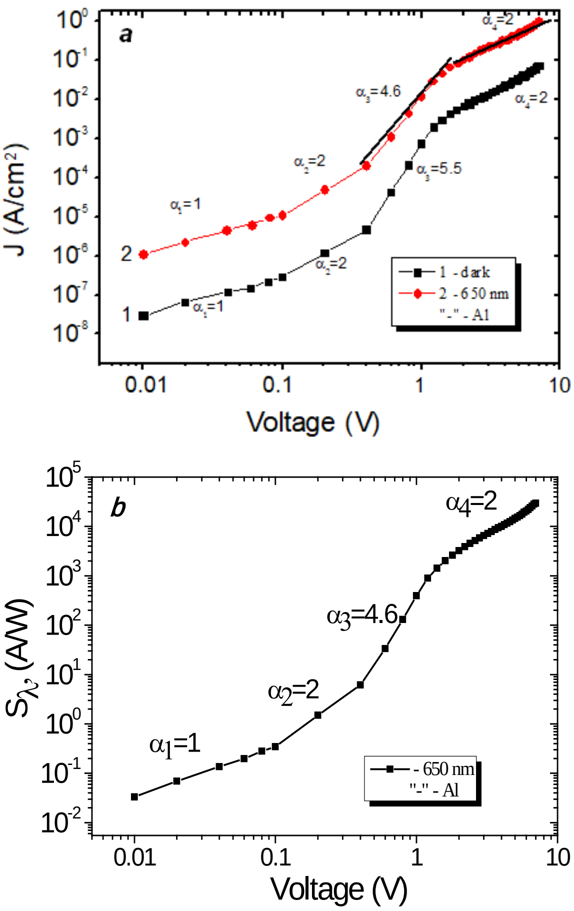

Fig. 2. Dependences of the current density J (a) and current photosensitivity S_λ (b) of the Al–Al$_2$O$_3$–p-CdTe–Mo structure on the forward bias voltage in the darkness (*1*) and under illumination with the monochromatic light λ = 650 nm (*2*). T = 300 K.

sharp increase of current, $J \sim V^\alpha$, where α = 4.6, and the second quadratic one with $J \sim V^2$ do not fit in this model. Apparently, recombination processes occur through composite complexes.

The mentioned complexes can be of various nature, namely: donor-acceptor pairs, impurity + vacancy complexes, impurity atom + interstitial defect, or Frenkel pair type defects formed as a result of recombination-stimulated or photo-stimulated processes. In [10], the models of such composite complexes are collected. At this, the recombination process through all similar two-level complexes is approximately the same as shown in Fig. 3.

It was also shown in [10] that the rate of recombination through all these complexes can be approximately expressed as follows:

$$U = N\frac{c_{n1}c_{p2}\left(pn - n_i^2\right)}{c_{n1}\left(n + n_{11}\right) + c_{p2}\left(p + p_{12}\right) + c_{12}\,pn}\,, \qquad (1)$$

where N is the concentration of complexes, c_{n1} is the electron capture coefficient at the level E_1, c_{p2} is the hole capture coefficient at E_2, n_{11} and p_{12} are the analogs of Shockley–Read statistical factors for the levels E_1 and E_2:

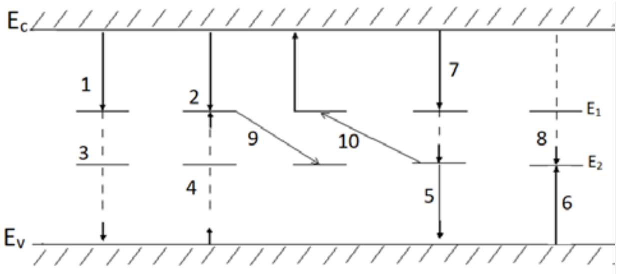

Fig. 3. Recombination through a two-level recombination complex. E_1 and E_2 are the energy levels of this complex. *1* – $c_{n1}N\left(1 - f_{R_1}\right)n$, *2* – $c_{n1}Nf_{R_1}n_{11}$ describe the exchange of the level E_1 with the conduction band. *3* – $c_{p1}Nf_{R_1}p$, *4* – $c_{p1}N\left(1 - f_{R_1}\right)p_{11}$ describe the exchange of the level E_2 with the valence band. *5* – $c_{p2}Nf_{R_2}p$, *6* – $c_{p2}N\left(1 - f_{R_2}\right)p_{12}$ describe the exchange of level E_2 with the valence band. *7* – $c_{n2}N\left(1 - f_{R_2}\right)n$, *8* – $c_{n2}Nf_{R_2}n_{12}$ describe the exchange of level E_2 with the conduction band. *9* – $c_{12}Nf_{R_1}\left(1 - f_{R_2}\right)$, *10* – $c_{12}Nf_{R_2}\left(1 - f_{R_1}\right)e^{\frac{E_2 - E_1}{kT}}$ describe the exchange of the level E_1 with the level E_2, *i.e.* intra-complex exchange. f_{R_1} and f_{R_2} are the probabilities of filling the levels E_1 and E_2 by electrons, respectively.

$$n_{11} = N_c e^{-\frac{E_c - E_1}{kT}}\,, \quad p_{12} = N_v e^{-\frac{E_2 - E_v}{kT}}\,.$$

In the expression (1), the latter term in the denominator describes the intra-complex electron exchange. When this term is small, *i.e.*

$$c_{12}\,pn << c_{n1}\left(n + n_{11}\right) + \left(p + p_{12}\right), \qquad (2)$$

the expression (1) practically coincides with the typical expression of Shockley–Read statistics. In this case, the I–V characteristic for a sufficiently long diode (d/L >> 1) is described by the well-known Lampert law, $J \sim V^2$. However, as shown in [10], when this term becomes significant, the Lampert law is replaced by a stronger dependence $J \sim V^\alpha$ with $\alpha > 2$. When the intra-complex exchange of non-equilibrium carriers becomes predominant, the sign of the inequality (2) reverses, and the recombination rate U saturates, as can be seen from (1). In this case, the segment with the dependence $J \sim V^2$ appears again in the I–V characteristic [10]. These theoretical predictions are in good agreement with the experimental results described in detail in [9].

Now let us analyze in more detail the segments of the light I–V characteristic to determine the dynamics of photosensitivity increase with the bias voltage. The linear segment of the I–V characteristic is defined by the resistance of base, since the current transport is formed by equilibrium carriers there. It is known that the resistance for a linear segment practically coincides with that of a photoresistor made of the same base material as the injection photodiode and having the same dimensions.

The spectral integrated photosensitivity of the injection photodiode and the photoresistor corresponding to this segment of the *I–V* characteristic almost coincide. As can be seen in Fig. 2b, the maximum value of the current sensitivity in the linear segment $S_\lambda = 0.34$ A/W, which is much smaller than that of an ideal photodetector ($S_\lambda = 0.51$ A/W) at the given wavelength of electromagnetic radiation. When the condition $n > n_0$ is satisfied (here, n and n_0 are the concentrations of injected and equilibrium electrons, respectively), the current in the structure is mainly determined by non-equilibrium carriers generated by incident light and injected from the contact. The quadratic segment of the *I–V* characteristic is caused by modulation of semiconductor with injected charge carriers during their bipolar drift in the electric field [10]. The maximum value of the spectral sensitivity in this segment $S_\lambda = 6.1$ A/W, which is ~12 times higher than the sensitivity of an ideal photodetector ($\lambda =$ 650 nm). This photosensitivity value is achieved at $V = 0.4$ V. At this bias voltage, the photosensitivity of a similar photoresistor is ~ 1.3 A/W, which is approximately five times lower than that of the injection photodiode. The magnitude of the current sensitivity of photoresistor at high bias voltages was obtained by extrapolating the linear part of the dependence $S_\lambda(V)$. The increase of bias voltage above the value $V = 0.4$ V leads to the sharp increase of the photosensitivity of photodiode. For example, when V increases by only three times, from 0.4 to 1.2 V, S_λ increases by 150 times, and the photocurrent also increases by approximately the same proportion (see Fig. 2a). As indicated above, in these limits of V the current-voltage characteristic is described by a power-law dependence $J \sim V^\alpha$, where $\alpha = 4.6$, *i.e.* has a segment of the sharp increase of current. For a stationary external signal, the coefficient of injection amplification K is the ratio defined by formulas (6)–(10) in [5]. The obtained results enable to conclude that the steepness of *I–V* characteristic also plays a decisive role on formation of the photosensitivity of injection photodiodes in addition to modulation of the base resistance by carrier injection. It is defined by the mechanism of current transport, which is confirmed experimentally (see Fig. 2b). At the end of the third segment in the dependence $S_\lambda(V)$, the coefficient of injection amplification reaches the value ~ 250. The coefficient K reaches the highest value equal to ~1350 in the fourth segment of the light *I–V* characteristic, when recombination through composite complexes reaches full saturation. Thus, amplification of photoelectric injection under illumination with “own” light in injection photodiodes made of high-resistance highly compensated *p*-CdTe films, is achieved according to the positive feedback (PF) mechanism.

Next, let us consider amplification of primary photocurrent under illumination with “impurity” light. According to a theoretical analysis, when the base conductivity is determined by carriers injected from contacts under the “impurity” illumination, this amplification is associated with immediate μ-modulation of mobility, *i.e.* is parametric. Taking this circumstance into account, this deformation of spectral sensitivity at different voltages (see Fig. 1a) can be explained as follows. The amplification coefficient of radiation receivers is defined as the ratio of photocurrent (output current of photodetector) expressed as the quantity of electrons per second, to the number of photons absorbed during the same time. It is believed that each absorbed photon generates non-equilibrium charge carriers. Under the “intrinsic” illumination, the amplification coefficient of photoresistor is equal to [5]

$$K_r = \frac{\tau_n}{t_n} + \frac{\tau_p}{t_p}, \tag{3}$$

where τ_n and τ_p are the times of the flight of electrons and holes through the base of the diode. Under “impurity” illumination, only one term remains in (3).

The photoelectric amplification coefficient of the injection photodiode with the *I–V* characteristic corresponding to (3) under “impurity” illumination (for example, if $p_{ph} >> n_{ph}$) is equal to [5]:

$$K = \frac{9}{8}\frac{\tau_n}{t_n}\frac{\tau_p}{t_p}. \tag{4}$$

The coefficient K exceeds the amplification for the impurity photoresistor by the amplification of the generation current of minority charge carriers. The ratio τ_n/t_n for IPD based on a *p*-type semiconductor is the coefficient of the amplification of photoelectric injection at the drift transport mechanism of non-equilibrium charge carriers in the diode base. Hence, the sensitivity of diode structures to light can be enhanced by tens, hundreds and thousand times due to injection amplification.

Let us consider next the photoelectric amplification in the injection photodiode based on a high-resistance highly compensated *p*-CdTe film under “impurity” illumination ($\lambda = 950$ nm) as a function of injection level (Figs 4a and 4b). It can be clearly seen from these figures that the light *I–V* characteristics under “impurity” illumination are described by the same dependences as the *I–V* characteristic in the dark. They differ only in the magnitude of current at the same value of bias voltage as well as in the magnitude of exponent α in the segment of sharp increase of current (see Fig. 4). According to Fig. 4b, at the end of linear segment of the light *I–V* characteristic, when the structure operates as a photoresistor, the spectral photosensitivity is very low ($S_\lambda = 0.05$ A/W). This shows that there is almost no amplification of primary photocurrent in the photoresistor mode. Consequently, the photoelectric injection amplification coefficient of diode is $\tau_n/t_n = 1$. The electron mobility is found to be $\mu_n \approx 40\ \text{cm}^2\cdot\text{V}^{-1}\cdot\text{s}^{-1}$ at the $\tau_n \approx 2.5\cdot10^{-9}$ s and $d = 10$ μm (the base thickness). We consider next the methods for determination of the value of τ_n in detail. The electron mobility calculated in this way, which is almost half of that for a single crystal, is quite acceptable for polycrystalline cadmium telluride.

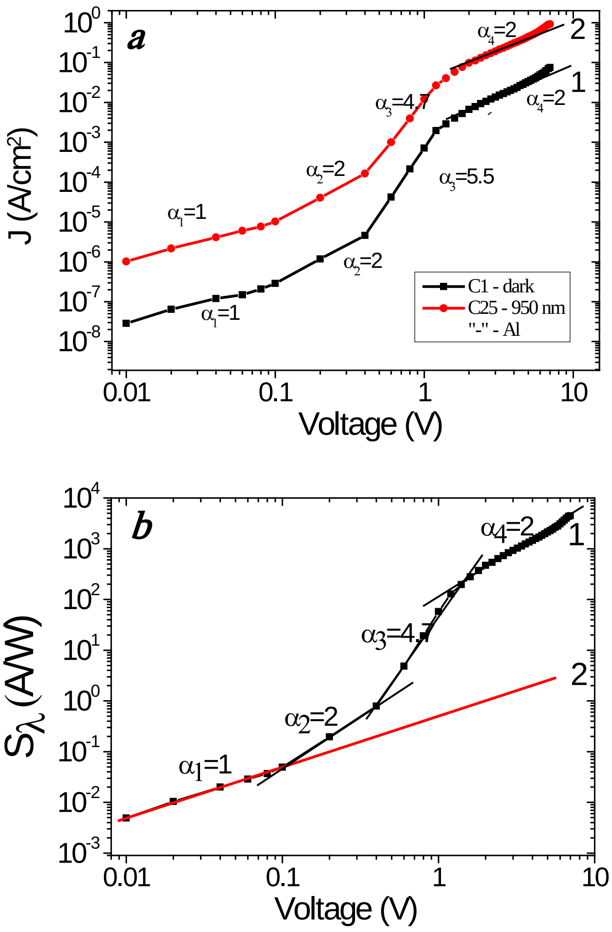

Fig. 4. Dependences of the current density J (a) and current photosensitivity S_λ (b) of the Al–Al$_2$O$_3$–*p*-CdTe–Mo structure on the forward bias voltage in the darkness (*1*) and under the illumination with the monochromatic light $\lambda = 950$ nm (*2*). $T = 300$ K.

In the quadratic segments of the light *I–V* characteristics, the conductivity of the base of the injection photodiode is modulated by light and injected charge carriers. In this segment, the photosensitivity value increases from 0.05 up to ~ 0.8 A/W, *i.e.*, to the photosensitivity value of an ideal photodetector (0.76 A/W). According to the theory [5], parametric amplification of primary photocurrent occurs due to the modulation of bipolar mobility. Since the base of the studied injection photodiode is highly resistive (highly compensated *p*-CdTe), "impurity" illumination, modulating filling of deep acceptor centers, generates photoelectrons that change the difference in carrier concentrations. The numerator of the following expression:

$$\mu = \frac{n - p\dfrac{dn}{dp}}{n\mu_n + p\mu_p}\mu_n\mu_p \tag{5}$$

depends on the difference between the concentrations of charge carriers, which, in turn, determine modulation of bipolar drift mobility μ, leading to a strong change in the concentration of charge carriers entering from the contacts. From this segment, we try to determine the change of bipolar mobility with the change of current. For this, we find the value of photoelectric amplification coefficient for the injection photodiode corresponding to the end of the first quadratic segment, substituting the values of current sensitivity of the injection photodiode and similar photoresistor in the expression at a voltage $V = 0.4$ V (see Fig. 4b). We obtain $K = 4.5$. At the same time, the theoretical photoelectric amplification coefficient of the injection diode [5] is expressed as $K = \tau_n/t_n$. Therefore, $4.5t_n = \tau_n$ or

$$\mu = \frac{4.5L^2}{V\tau_n}. \tag{6}$$

Substituting the values $L = 10$ μm (thickness of the diode base), $U = 0.4$ V and $\tau_n \approx 3\cdot10^{-9}$ s into Eq. (6), we obtain $\mu \approx 3.7\cdot10^2$ cm$^2\cdot$V$^{-1}\cdot$s^{-1}. The value of τ_n was determined using two ways: i) from the quadratic segment of the light *I–V* characteristic according to the Lampert law, which resulted in [10] $\tau_n \approx 2.5\cdot10^{-8}$ s, and ii) from the value of the relaxation current of non-equilibrium carriers at low excitation level both in the absence of voltage and at different applied voltages [1]. Non-equilibrium carriers were excited by a П-shaped electric signal with an amplitude of 60 to 80 mV and duration of 100 to 200 μs supplied from a calibrated pulse generator G5-55. The steepness of these pulses was no higher than $2\cdot10^{-9}$ s, one-pulse not less than $5\cdot10^{-4}$ s.

The relaxation curve for the concentration of non-equilibrium electrons at different voltages is described by an exponential dependence in the following form:

$$\Delta n = n_1 e^{-\frac{t}{\tau}}, \tag{7}$$

where t is the time and τ is the constant of relaxation time, respectively. The values of the time constant determined from the expression (7) are $\tau_1 \approx 3\cdot10^{-8}$ s in the absence of voltage and $\tau_2 \approx 10^{-7}$ s at a constant voltage $V = 1.2$ V corresponding to the end of segment of the sharp current increase.

As can be seen from Fig. 4a, the segment of *I–V* characteristic described using the Lampert law is followed by the one of the sharp increase of current, corresponding to recombination of non-equilibrium carriers through composite complexes, inside which electronic exchange takes place. As a result, the recombination process slows down in time, as if the lifetime of minority charge carriers increased. Apparently, this change in recombination leads to a sharp increase of current sensitivity in the segment of sharp current increase under "impurity" illumination. To make a final confirmation, we carried out the following estimation. First, we determined the current sensitivities of the injection photodetector and photoresistor. Calculating their ratio, we found the injection amplification of the photodetector to be $K \approx 290$. On the other hand, $K = \tau_n/t_n$. Therefore, one can write:

$$K = \tau_n/t_n \approx 290. \tag{8}$$

Substituting the value $\tau_n \approx 3\cdot10^{-7}$ s determined from the relaxation curve at $V = 1.2$ V in (8), we found that the drift mobility at the end of segment corresponding to the sharp increase of current in the light current-voltage characteristic is approximately $8\cdot10^2$ cm^2/V·s. It may be concluded that the injection amplification of the photodetector corresponding to this section of the light current-voltage characteristic is mainly determined by the increase of photodetector inertia. That is, the recombination processes through composite complexes, within which electronic exchange takes place, lead to the delay of non-equilibrium carriers and the inertia increase. As known from theory [10], the rate of recombination through composite complexes is saturated in the fourth segment of the light *I–V* characteristic. Therefore, the time characteristics of the photodetector remain constant. The injection amplification of the photodetector increases only due to the increase of bipolar drift velocity. Estimates show that the increase of this velocity in this segment is achieved by only the increase of field.

4. Conclusion

Study of the dependence of the spectral distribution of photosensitivity on the injection level at high bias voltages shows that this sensitivity reaches its maximum value $S_\lambda = 8.4\cdot10^4$ A/W under illumination with "own" light of $\lambda = 450$ nm at $V = 7$ V. $S_\lambda = 4.3\cdot10^4$ A/W under illumination with "impurity" light of $\lambda = 950$ nm at the same bias voltage. It has been found out that the positive feedback mechanism is realized, when the structure is illuminated with "own" light, while the parametric amplification mechanism is realized under illumination with "impurity" light.

References

1. Uteniyazov A.K., Leyderman A.Y., Gafurova M.V., Juraev Kh.N. and Dauletov K.A. The effect of ultrasonic treatments on current transport processes in Al-Al$_2$O$_3$-*p*-CdTe-Mo structure. *Advances in Materials Science and Engineering*. 2021. **2021**. Article ID 8836368, 6 p. https://doi.org/10.1155/2021/8836368.
2. Mirsagatov Sh.A., Muzafarova S.A., Baiyev M.S., Achilov A.S. The study of real structures of a diode with a Schottky barrier Al-*p*-CdTe. *Uzb. Phys. J.* 2010. No 12. P. 154–160.
3. Achilov A.S., Zaveryukhin B.N., Kalanov M.U., Rustamova V.M. X-ray studies structures of a new type of A$_2$B$_6$ electromagnetic radiation receiver. *Reports of the Academy of Sciences of RUz*. 2014. No 2. P. 24–26.
4. Uteniyazov A.K., Ismailov K.A. The spectral distribution of photosensitivity of Al-Al$_2$O$_3$-*p*-CdTe-Mo structure. *Reports of the Academy of Sciences of RUz.* 2019. No 5. P. 27–31.
5. Vikulin I.M., Kurmashev Sh.D., Stafeev V.I. Injection-based photodetectors. *Semiconductors*. 2008. **42**. P. 112–127. https://doi.org/10.1134/S1063782608010168.
6. Stafeev V.I. Structure and properties of Cd$_x$Hg$_{1-x}$Te-metal contacts. *Semiconductors*. 2009. **43**. P. 608–611. https://doi.org/10.1134/S1063782609050133.
7. Kurmashev S.D., Stafeev V.I., Vikulin I.M., Sofronkov A.N. Injection-amplification IR-photodiodes. *Proc. SPIE*. 1997. **3182**. https://doi.org/10.1117/12.280470.
8. Uteniyazov A.K. Photoelectric injection amplification of Al–Al$_2$O$_3$–p-CdTe–Mo structures at low bias voltages. *Karakalpak Scientific Journal*. 2020. **3**, Issue 2. Article 5. https://uzjournals.edu.uz/karsu/vol3/iss2/5.
9. Mirsagatov Sh.A., Uteniyazov A.K. The mechanism of current transport in the structure Al–*p*-CdTe–Mo with different thickness of the base. *Phys. Surface Eng*. 2015. **13**, No 3. P. 325–329. http://dspace.nbuv.gov.ua/handle/123456789/108760.
10. Uteniyazov A.K., Leyderman A.Yu., Ayukhanov R.A., Esenbaeva E.S., Gafurova M.V. Features of current transport in Al–Al$_2$O$_3$–*p*-CdTe–Mo structure. *SPQEO*. 2020. **23**, No 4. P. 339–345. https://doi.org/10.15407/spqeo23.04.339.

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Ismailov K.A.: resources, writing – reviewing and editing.
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Dauletmuratov B.K.: making inserts, writing – reviewing and editing.
Kamalov A.B.: visualization, verification and editing.

Підсилення фотоелектричної інжекції у фотодіоді на основі великозернистих плівок телуриду кадмію

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Анотація. Наведено результати досліджень підсилення фотоелектричної інжекції у структурі $Al–Al_2O_3–p$-CdTe–Mo при високих напругах зміщення прямого струму. Показано, що спектральна чутливість досягає максимального значення $S_\lambda = 8,4\cdot10^4$ А/Вт при освітленні «власним» світлом з $\lambda = 450$ нм та при $V = 7$ В, у той час як при освітленні «домішковим» світлом з $\lambda = 950$ нм $S_\lambda = 4,3\cdot10^4$ A/W при тій самій напрузі зміщення. Установлено, що при освітленні конструкції «власним» світлом реалізується механізм позитивного зворотного зв’язку, а при освітленні «домішковим» – механізм параметричного підсилення.

Ключові слова: напівпровідникова плівка, фотодетектор, чутливість, вольт-амперна характеристика.